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By Frank H. Rogers

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Modern Hydraulic Turbines Show High Efficiency

Review of Actual Performance Indicates High Efficiency Under Many Conditions of Service and Design. By Frank H. Rogers*

IN THE development of power from whatsoever source, a fundamental consideration is the efficiency of the machinery used. At first thought it might appear that such a statement should not apply to water power development, as water power is inexhaustible, but it must be remembered that the yearly flow available for any development is limited. Neglecting load conditions, the power which can be developed with this flow,

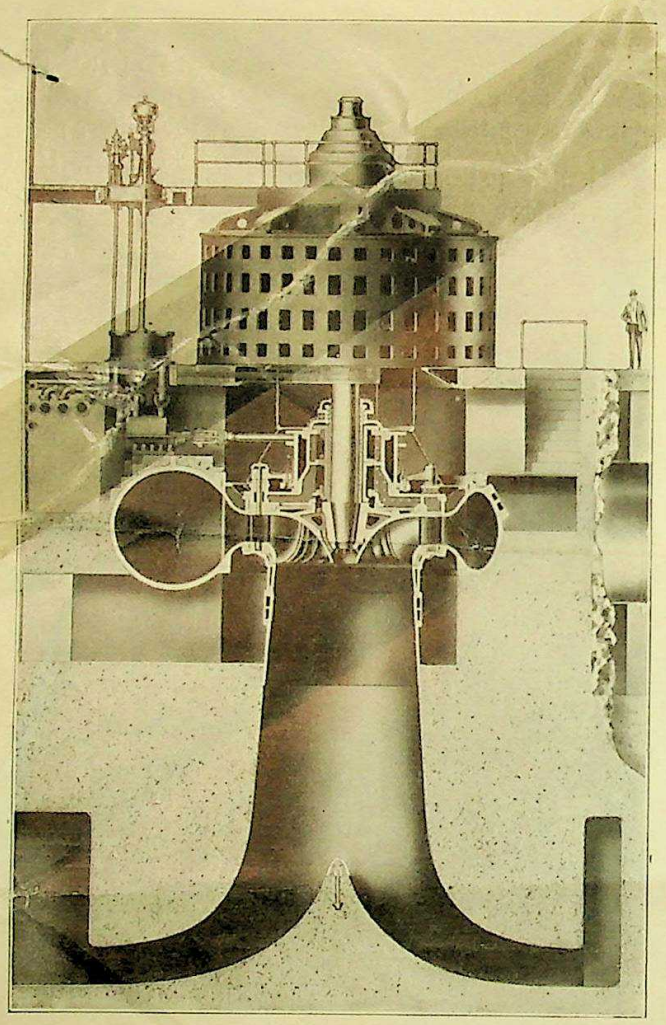

FIG. 1. A CROSS SECTIONAL VIEW OF ONE OF THE 37,500 HP. NIAGARA UNITS

and hence the earning power of a hydraulic plant, is directly proportional to the efficiencies of the turbines.

These conditions have been thoroughly appreciated for some years past with the result that large sums of money have been spent by the turbine manufacturers in the building of laboratories and the construction and testing of model turbines, and by the power companies in complete tests made on the large units after installation. Tests on models, though of considerable value to the designer, can not, in themselves, be relied upon in predicting the performance of the large units in place. There are instances of failure of turbines in plants, the success of which seemed assured when predicated on the performance of the models.

Many factors enter into this complicated problem but it may be of interest here to mention a few points which undoubtedly affect the comparative performances of the models and the large units:

(1) The model units are usually tested in an open flume setting, whereas the large units are provided with a closed casing, usually of the volute type.

(2) Frequently, the model units are tested with a straight tapering draft tube and the large units are installed with a curved tube, a spreading tube, or some other form.

(3) The head available in the laboratory is low, usually being from 8 to 15 ft., while the head on the large unit may have any value from 8 to 800 ft.

It is believed that this third factor is of particular importance in its effect on flow conditions within the draft tube. In the laboratory the static draft head, as well as the velocity head at the runner discharge, is low, so that the total draft head at the top of the tube is very conservative, its value being say 8 to 10 ft. In the large installation, the static draft head is usually much greater and the velocity head, increasing directly with the total head on the plant, may easily reach such a value that the total draft head at the top of the tube will be equal to 26 or 28 ft.

Water usually discharges from the runner as a whirling mass, the velocity varying across the tube, and there is a tendency for eddies to form, especially at the center of the tube. For the above reasons, the total draft head across the tube is not uniform and regions of low pressure occur where the vacuum is higher than the average. It is, therefore, evident that, in large installations where the average total draft head is high, the local vacuum at certain points may closely approach or even tend to exceed the barometric column. Such conditions are likely to produce eddies and whirls which do not conform to the general stream line flow and this discontinuity of flow often results in the impairment of power and efficiency, corrosion of runner, vibration and unstable operating conditions. In the small model units, however, where the total draft head is necessarily low, there is little danger of exceeding the barometric column at any point and there is less likelihood of eddies and whirls forming.

For the above reasons, the conditions of flow at the top of the draft tube may be quite different in the large installation under the high head as compared to the small model turbine under the low head. These points must be given particular consideration when attempting to predict the performance of the large units from the results obtained on the model units.

The real problem confronting the turbine designer is the selection of the proper form of draft tube, which will receive the water discharged from the runner in such a way as to prevent the formation of eddies and whirls under the high-vacuum conditions existing. Experience has shown that the symmetrical annular form

*Chief Engineer, I. P. Morris Dept., Wm. Cramp & Sons Ship & Engine Building Co., Philadelphia, Pa.

of tube meets these requirements as it preserves the continuity of flow existing in the runner throughout the draft tube.

The efficiency of an actual turbine installation can be correctly evaluated only by the actual performance of the unit in place. In recent years a great many tests have been conducted by engineers of the power companies and some of these results have been published. Such information is not only of great value to the power company making the tests and the manufacturer who furnished the turbines but also to all engineers in this field of engineering. It would be highly desirable and beneficial, if all the results, which had been obtained on the large units in place, were published, as such actual results are of far more value to the engineers of the power company contemplating a new installation than the guarantees or results of model tests which are presented by the turbine manufacturer with his bid.

law of motion, which may be stated that "the impulse or the product of force by time is equal to the change of momentum or the product of the mass by the velocity change":

$$F\,d\,t = M\,d\,v \quad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

To apply this principle to the determination of the quantity of water flowing in a pipe of uniform cross-section, consider that the guide vanes of the turbine at the lower end are closed gradually in a given time, so that the velocity of the water in the pipe is gradually diminished and is finally stopped when the guide vanes are fully closed. During closure, the pressure in the pipe rises and this pressure rise is the manifestation of the force exerted to stop the flow of the mass of water in the pipe. From the fundamental equation (1), if the mass of water in the pipe is known and the time taken to stop its flow and the average force exerted in doing so are measured, the velocity of the water, prior

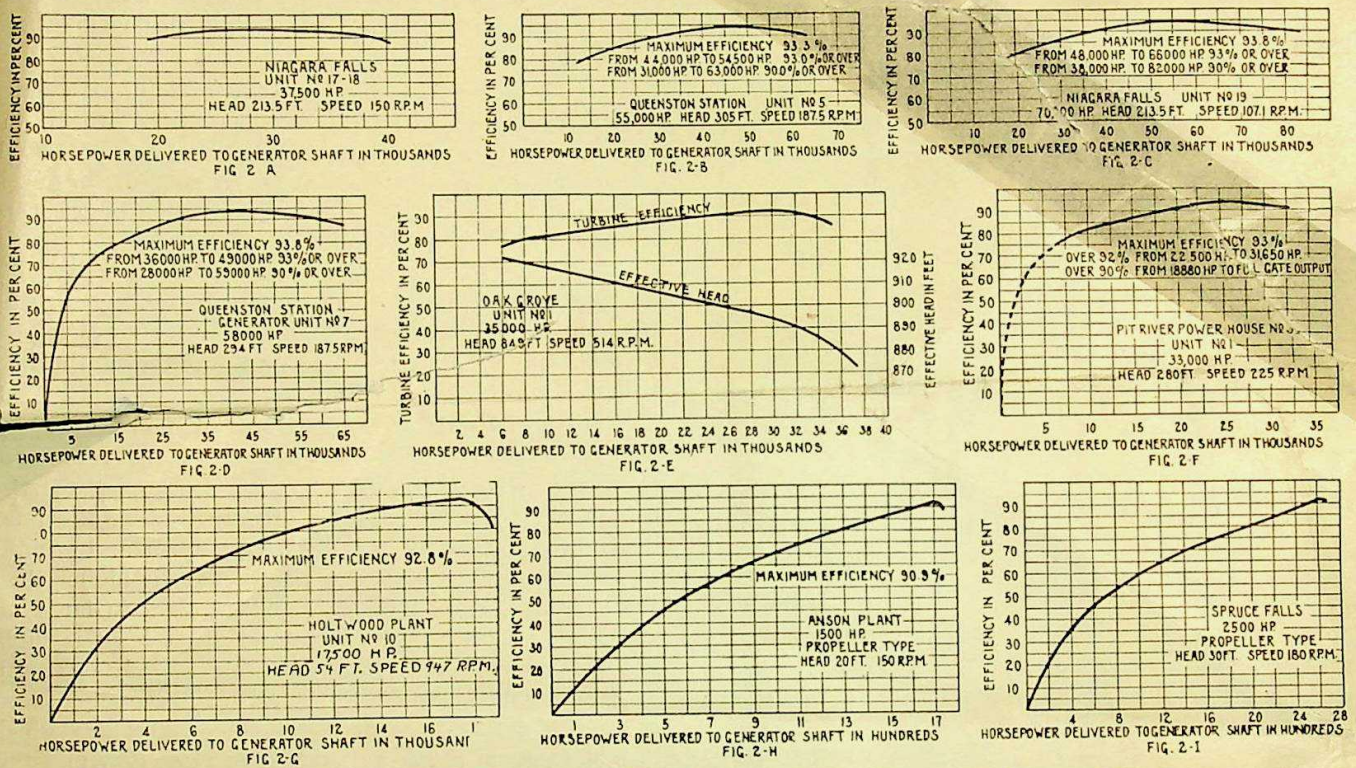
EFFICIENCY IN PER CENT
NIAGARA FALLS
UNIT Nº 17-18
37,500 HP
HEAD 213.5 FT. SPEED 150 R.P.M.
HORSEPOWER DELIVERED TO GENERATOR SHAFT IN THOUSANDS
FIG. 2-A
MAXIMUM EFFICIENCY 93.3%
FROM 44,000 HP. TO 54,500 HP. 93.0% OR OVER
FROM 31,000 HP. TO 63,000 HP. 90.0% OR OVER
QUEENSTON STATION UNIT Nº 5
55,000 HP. HEAD 305 FT. SPEED 187.5 R.P.M.
FIG. 2-B
MAXIMUM EFFICIENCY 93.8%
FROM 48,000 HP. TO 66,000 HP. 93% OR OVER
FROM 38,000 HP. TO 82,000 HP. 90% OR OVER
NIAGARA FALLS UNIT Nº 19
70,000 HP. HEAD 213.5 FT. SPEED 107.1 R.P.M.
FIG. 2-C
MAXIMUM EFFICIENCY 93.8%
FROM 36000 HP. TO 49000 HP. 93% OR OVER
FROM 28000 HP. TO 59000 HP. 90% OR OVER
QUEENSTON STATION
GENERATOR UNIT Nº 7
58000 HP
HEAD 294 FT. SPEED 187.5 RPM
FIG. 2-D
TURBINE EFFICIENCY
EFFECTIVE HEAD
OAK GROVE
UNIT Nº 1
15,000 H.P.
HEAD 84.5 FT. SPEED 514 R.P.M.
TURBINE EFFICIENCY IN PER CENT
EFFECTIVE HEAD IN FEET
FIG. 2-E
MAXIMUM EFFICIENCY 93%
OVER 92% FROM 22,500 H.P. TO 31,650 H.P.
OVER 90% FROM 18880 HP TO FULL GATE OUTPUT
PIT RIVER POWER HOUSE Nº 3
UNIT Nº 1
33,000 H.P.
HEAD 280 FT. SPEED 225 R.P.M.
FIG. 2-F
MAXIMUM EFFICIENCY 92.8%
HOLTWOOD PLANT
UNIT Nº 10
17,500 H.P.
HEAD 54 FT. SPEED 94.7 R.P.M.
FIG. 2-G
MAXIMUM EFFICIENCY 90.9%
ANSON PLANT
1500 H.P.
PROPELLER TYPE
HEAD 20 FT. 150 R.P.M.
FIG. 2-H
SPRUCE FALLS
2500 H.P.
PROPELLER TYPE
HEAD 30 FT. SPEED 180 R.P.M.
FIG. 2-I

FIG. 2. HYDRAULIC TURBINE DEVELOPMENT AS SHOWN BY EFFICIENCY CURVES

In this article the author presents the results of a number of tests, made in each case by the power company engineers, on some noteworthy installations in the United States and Canada and points out the special features of design which contributed largely to the actual results obtained.

The quantity of water flowing was, in most of the tests to be described, determined by either the "Gibson" method or by the "Salt Velocity" method. Both of these methods have been thoroughly tried out and found to give a high degree of accuracy and the results are generally accepted by both the power companies and the turbine manufacturers. It might be of interest, however, to mention briefly the principles involved.

The Gibson method* makes use of Newton's second

to the interruption of its flow, may be readily determined.

The second or Salt Velocity* method for measuring the flow of water has been developed by Prof. C. M. Allen of Worcester, Mass. The theory is simple and is expressed very clearly by Prof. Allen as follows:

"The Salt Velocity method of water measurement is based on the fact that salt in solution increases the electrical conductivity of water. Salt solution is introduced near the upper end of the conduit and the passage of the solution across one or more pairs of electrodes at other points in the conduit is recorded graphically by electrical recording instruments. The passage of the salt solution between two points is accurately timed and the volume of the penstock between the same points is

*This method is fully described in a paper "The Gibson Method and Apparatus for Measuring the Flow of Water in Closed Conduits," presented by Norman R. Gibson at the Annual Meeting of the A. S. M. E., in New York City, December, 1923.

*A complete description of this method and results of tests made are given in a paper "The Salt Velocity Method of Water Measurement," presented by Charles M. Allen and Edwin A. Taylor at the Annual Meeting of the A. S. M. E. in New York City, December, 1923.

accurately determined. The discharge in cubic feet per second equals the volume in cubic feet divided by the time in seconds."

37,500 Hp. Niagara Units Show Flat Efficiency Curves

Two 37,500-hp. vertical shaft turbines were built by the Cramp Co. in 1919 for the Niagara Falls Power Co. Each of these units is rated under 213.5 ft. head at a speed of 150 r. p. m. Figure 1 shows a sectional elevation through one of these units. These two units were tested by the power company, using the Gibson method for determining the flow. Figure 2 A shows the

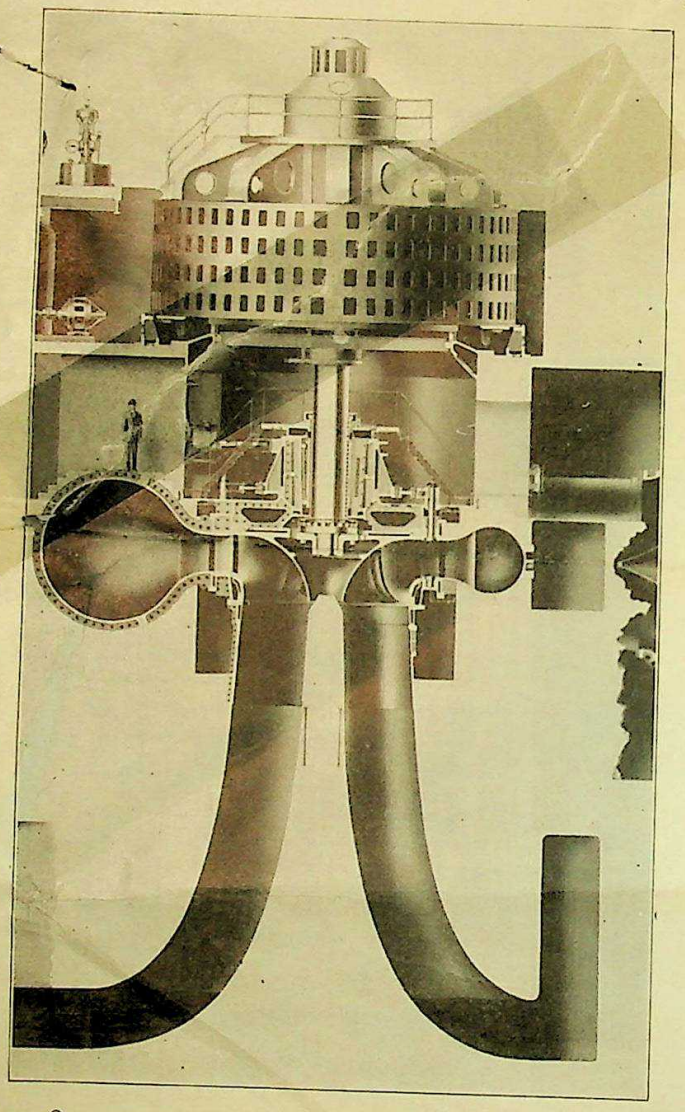

FIG. 3. CROSS SECTIONAL DRAWING OF 70,000-HP. UNIT WITH DRAFT TUBE CONE EXTENDING TO TURBINE RUNNER

performance of these units. The maximum efficiency secured was 93 per cent and the units developed 90 per cent or over from 20,000 to 39,000 hp. These excellent results and particularly the high average efficiency throughout the entire range of power were the result of careful design and construction of all parts of the units.

For example, a series of special model runners were developed and tested at Holyoke, from which the final runner design was selected. The casing, speed ring vanes and guide vanes were designed to conform to the stream line flow of the water. Labyrinth runner[illegible] were provided to reduce the leakage to a minimum and the Moody spreading draft tube was used to regain not only the axial velocity at the runner discharge but also the velocity of whirl.

For high head units such as these, at loads close to maximum efficiency, the water leaves the runner in an axial direction but, at part loads, a whirling component is developed. The extremely flat shape of the efficiency curve shows the adaptability of the Moody tube to regain efficiently the velocity of whirl.

Five 55,000-hp. Units Installed in Queenston Station

Each of the first five turbines installed in the Queenston station of the Hydro Electric Power Commission of Ontario had a rating of 55,000 hp. Three of these units were designed and built by the Cramp Co. rated at the above power under a head of 305 ft. at a speed of 187.5 r. p. m. These turbines are similar in general design to the 37,500-hp. Niagara units.

The efficiency test made on unit No. 5 was conducted by the Power Commission in the presence of both American and Canadian members of the Joint Control Commission for water diversion at Niagara Falls and results are shown in Fig. 2B. The Gibson method was used to determine the flow. It will be noted that these units developed a maximum efficiency of 93.3 per cent and also extremely high efficiencies over a wide range of power.

Queenston Station Completed with Four 58,000-hp. Units

Shortly after the installation of the first five units at Queenston, the demand for power in the Province of Ontario influenced the Commission to complete the station so that since that time four additional units, each rated at 58,000 hp., 294 ft. head, 187.5 r. p. m., were installed. These units were built by the Dominion Engineering Works, Ltd., of Montreal. This single plant, therefore, has an installed rated capacity of approximately one-half million horsepower.

Design is similar to the 55,000-hp. units but some improvements were made in the runner and casing. The most important change, however, was in the draft tube design. This tube is also of the Moody spreading type but is designed so that the annular form of water passage is maintained from the runner discharge to the bottom of the tube. To meet this requirement a high central concrete cone is provided, extending all the way up to the hub of the runner. The combination of the cone and outside spreading bell results in the proper sequence of areas in annular form, to regain the energy in the water discharged from the runner.

Entire absence of vibration, excellent regulating qualities and high efficiencies obtained on this unit are ample proofs of the excellence of this design of draft tube. The results of the efficiency test made on unit No. 7, given in Fig 2D, show a marked increase in the maximum efficiency and an extension to greater limits of the range of high efficiencies. It is believed that the maximum efficiency of 93.8 per cent obtained establishes a new world's record.

The latest and largest addition to the plants of the Niagara Falls Power Co. was started in 1923 and consisted of three 70,000-hp. units, two of which were built

Cramp Co. In less than five years, therefore, the record capacity of 37,500 hp. had been almost doubled. Each unit is rated at 70,000 hp. under 213.5 ft. head at 107 r. p. m. Many interesting and difficult problems had to be solved in the construction of these large units. Among the special features incorporated in the design are the Moody draft tube of continuous annular form, Taylor sectionalized casing, off-set operating gear, disc guide vanes, labyrinth runner seals and adjustable vitæ bearings. Figure 3 shows a sectional elevation through one of these units.

Official tests on these units were made by the Power Co., using the Gibson method for determining the flow, and these tests were witnessed and approved by the representatives of both the United States and Canadian Governments. Figure 2C shows the efficiency test on unit No. 19. The maximum efficiency of 93.8 per cent equals the record obtained on the Queenston unit No. 7 but the part load efficiencies were slightly better, being 90 per cent or over from 38,000 to 82,000 hp. It may safely be stated that this unit has established an unequalled record in hydraulic performance.

The four different installations so far described contain units of similar design but of different dimensions and operate under different heads. The similarity of the efficiency curves obtained in four independent tests is certainly a remarkable confirmation of their actual performance.

Oak Grove Unit Operates Under High Head

An interesting installation involving an extremely high head is the vertical shaft turbine built by the Pelton Water Wheel Co. for the Oak Grove plant of the Portland Electric Power Co. This unit is rated at 35,000 hp. under a head of 849 ft. at a speed of 514 r. p. m. It is believed that this is the highest head reaction turbine that has ever been constructed. Figure 4 shows an outside elevation of this unit.

Special features were incorporated in the design, the most interesting of which are probably the rubber seal rings, which were provided at the runner intake to reduce leakage, and the Moody spreading draft tube. The performance of this unit to date has been excellent both as regards mechanical operation and efficiencies developed.

The test of this unit was made by the Power Co., measuring the flow of water by Pitot tubes. The old method of making traverses was not used but a new method known as the "Multiple Pitot Tube" method was adopted. In this method a large number of fixed Pitot tubes and piezometer nozzles is used instead of one or two movable tubes. All of these tubes and piezometers connect to a multi-glass tube manometer. This manometer therefore indicates the velocity heads at the centers of each of the predetermined cross-sectional areas in the pipe line. Instantaneous readings of all the velocity heads are obtained by photographing the gage board.

Results of the official test are shown in Fig. 2E, from which it will be noted that a maximum efficiency was obtained of 91 per cent, which is extremely good considering the high head under which this turbine operates and the relatively small dimensions of the water passages.

Another western installation recently put in operation and tested is the 33,000-hp. turbine built by the Pelton Water Wheel Co. for the Pacific Gas & Electric Co.'s Pit River Power House No. 3. The nominal rating of this unit is 29,000 hp. under a head of 280 ft, at a speed of 225 r. p. m. The unit is provided with rubber seal rings at the runner, disc guide vanes and Moody tube.

Acceptance test was made for the power company by Prof. C. M. Allen, determining the flow by the Salt Velocity method. The results, shown in Fig. 2F, are remarkable for a unit of this size in respect to both maximum efficiency and shape of curve, and establishes a Western record, which has been beaten in the East only by larger size units.

20,000-hp. Holtwood Units Designed for Limited Space

The Holtwood plant of the Pennsylvania Water & Power Co., started in 1907, was designed to contain ten

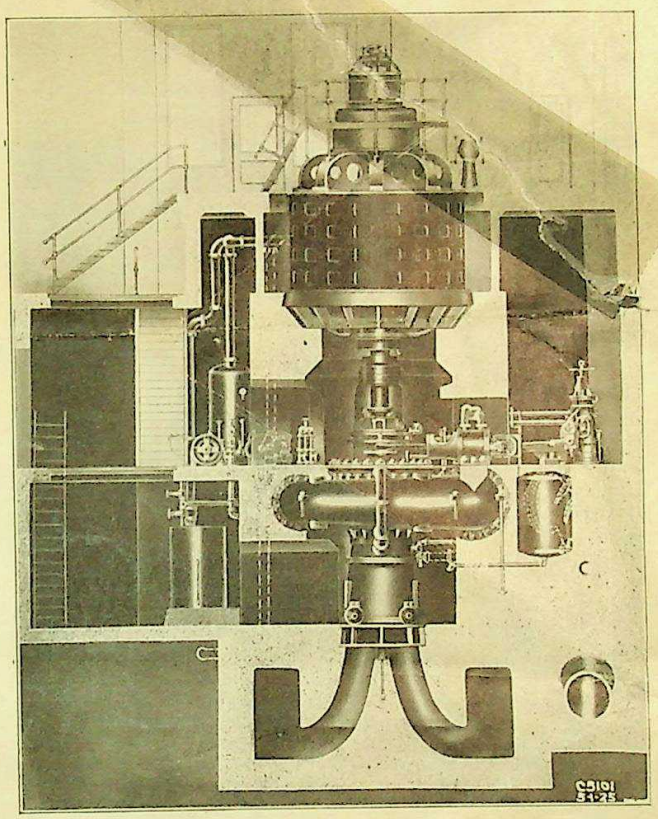

FIG. 4. ILLUSTRATING CONTROL AND INSTALLATION DETAILS OF THE OAK GROVE HIGH HEAD UNIT

units, each of the vertical shaft two-runner type. The foundations for all ten of these units were constructed in the initial development but, when the two final units were installed in 1923 and 1924, it was decided to abandon the early designs and to put in a single-runner unit in order to obtain greater power and higher efficiency. As the foundations were already in place, the space available was limited and, as it was desired to increase the capacity of the last two units by about 25 per cent over the former units, it was necessary to change materially the design of both the volute casing and the draft tube. The draft tube adopted was of the Moody spreading type with high cone and spiral collector passages. Each of the two new units was rated at 20,000 hp. under